University of BRISTOL

Bristol Composites Institute (ACCIS)

ADVANCED COMPOSITES COLLABORATION FOR INNOVATION & SCIENCE

Recent developments in experimental path-following

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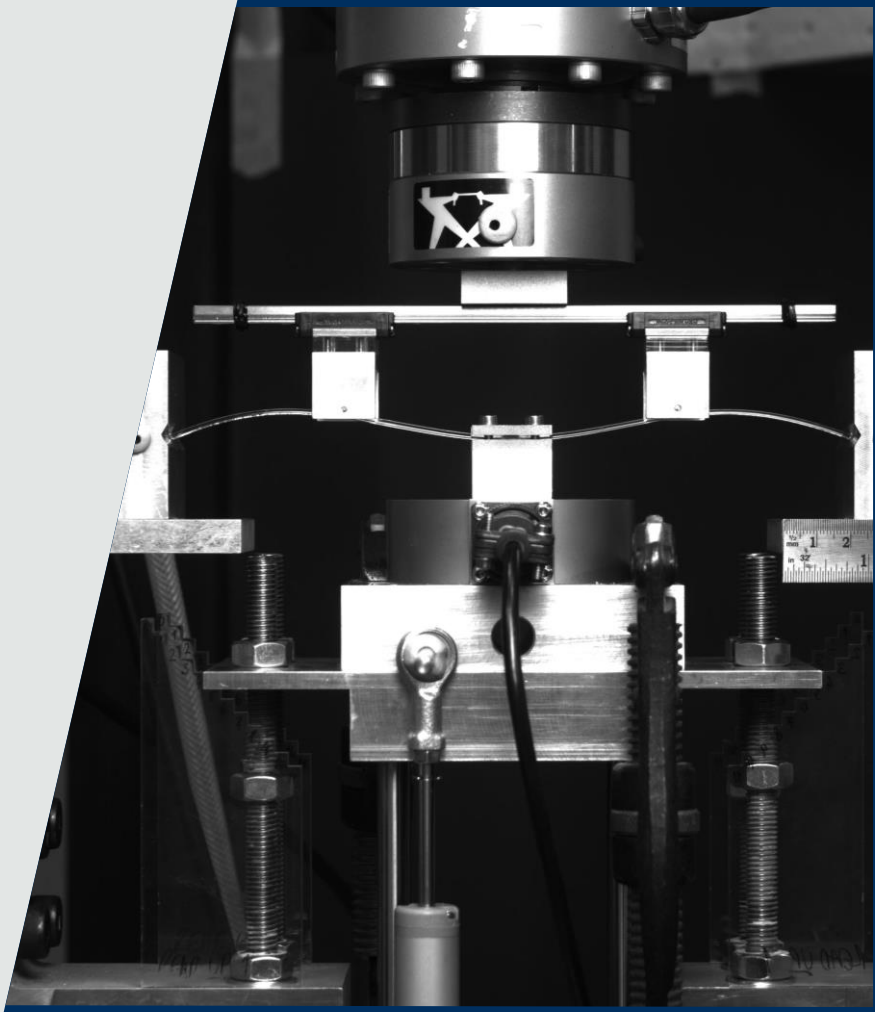

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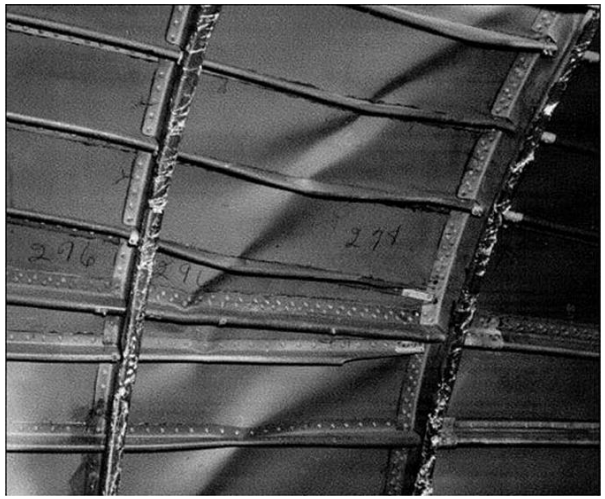
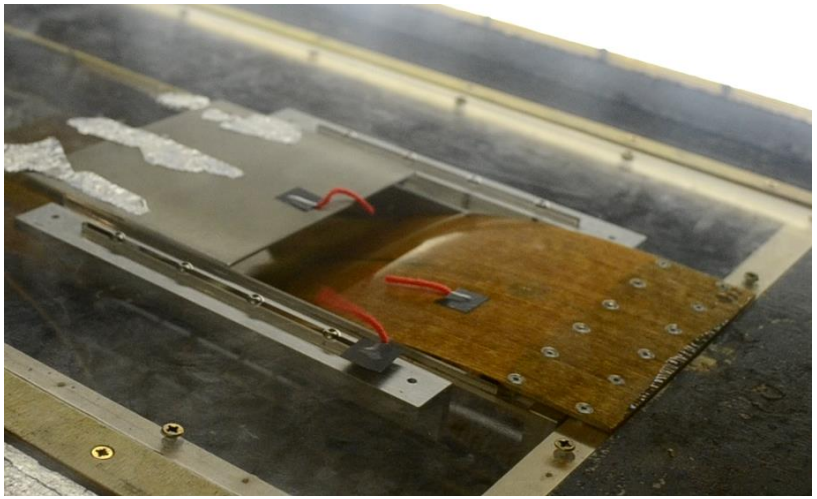
Nonlinear structures

- Buckling is well understood as a failure mechanism
- In some cases can be used to enable additional functionality





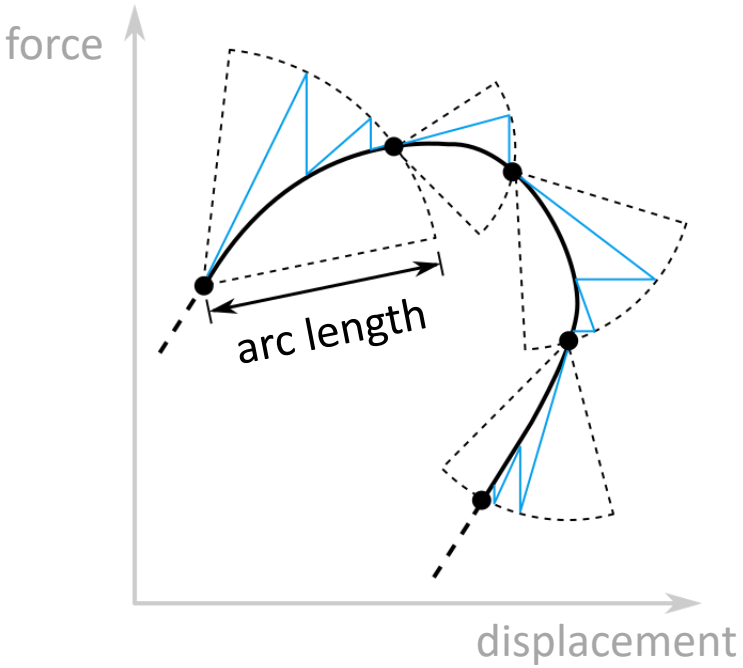
[1]

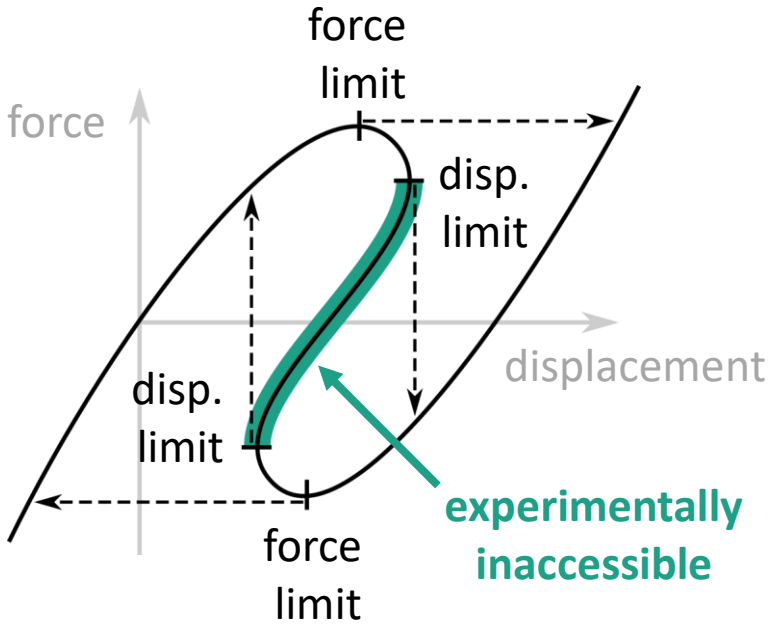
- Difficult to certify as few (if any) testing standards exist for nonlinear structures

[1] G. Arena *et al,* Proc. R. Soc. A, 2017.

The problem

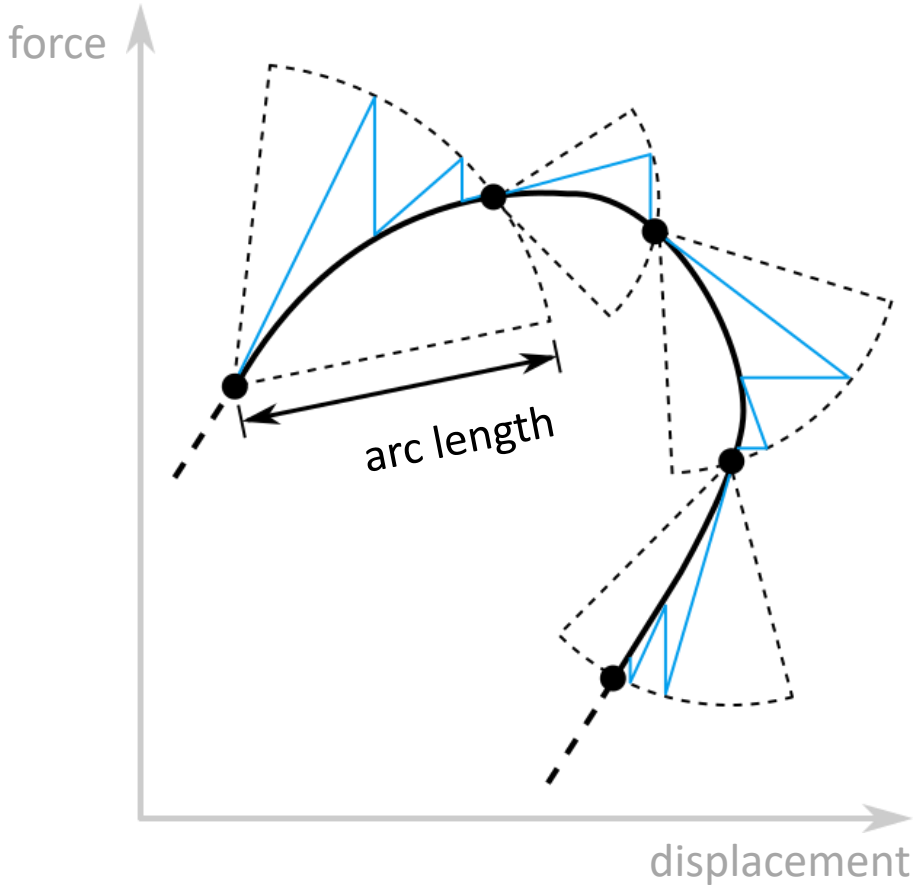
- Nonlinear numerical methods >> experimental methods
- Structures snap (experimenter loses control over structure)



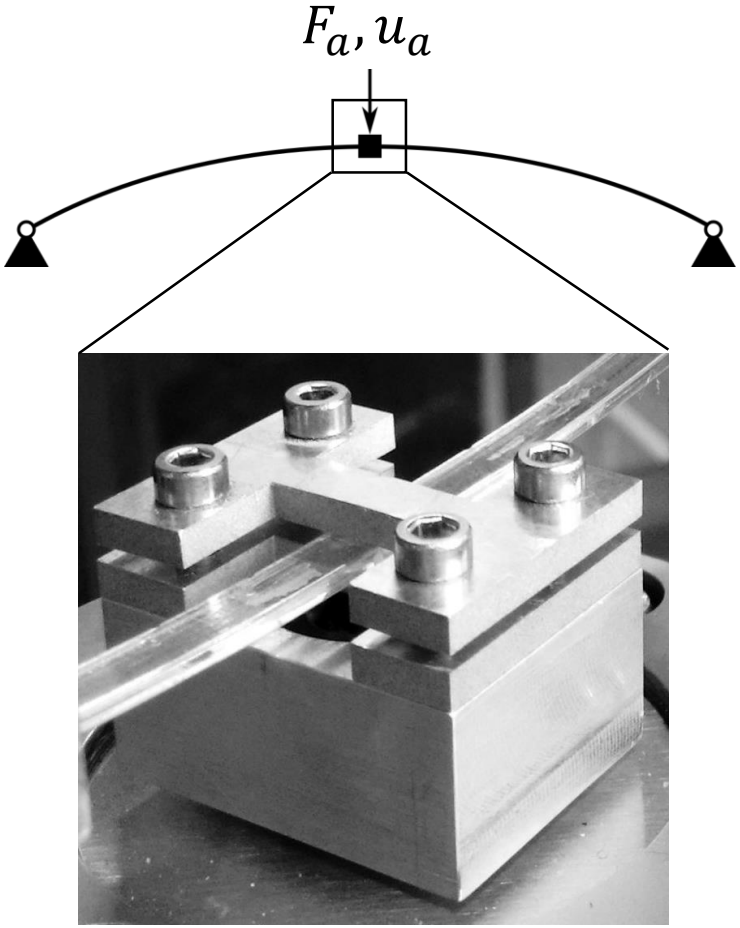


The question

Can we do this *experimentally*?

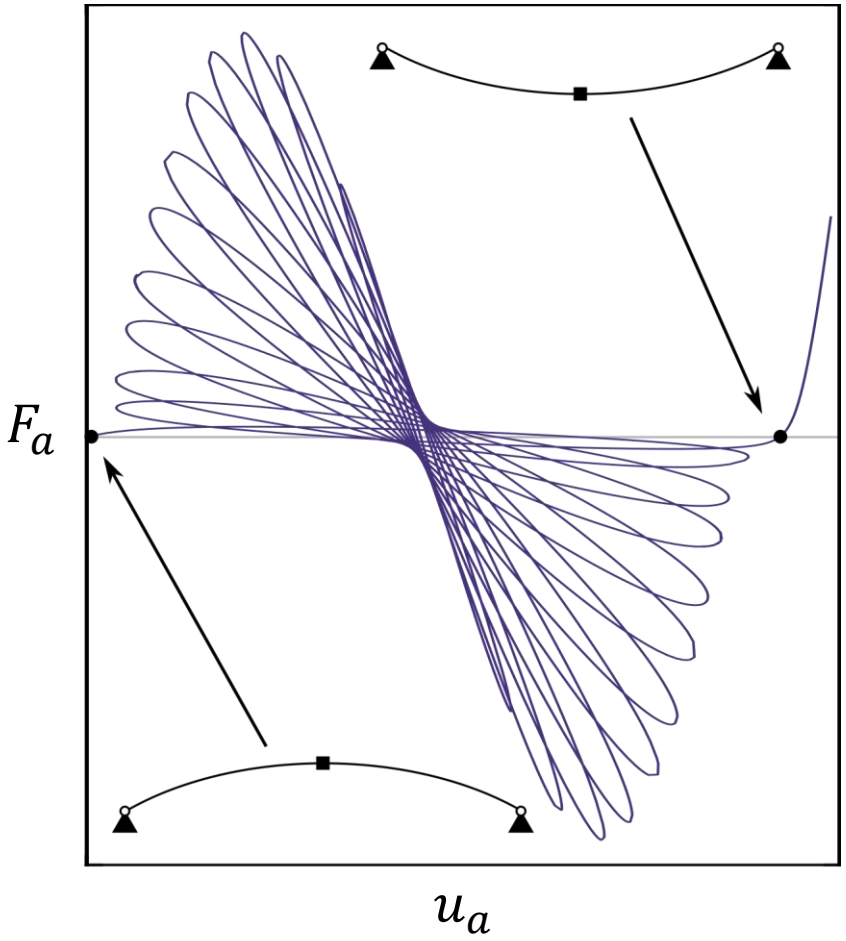


Test case: the shallow arch



Enforcing symmetry at the actuation point

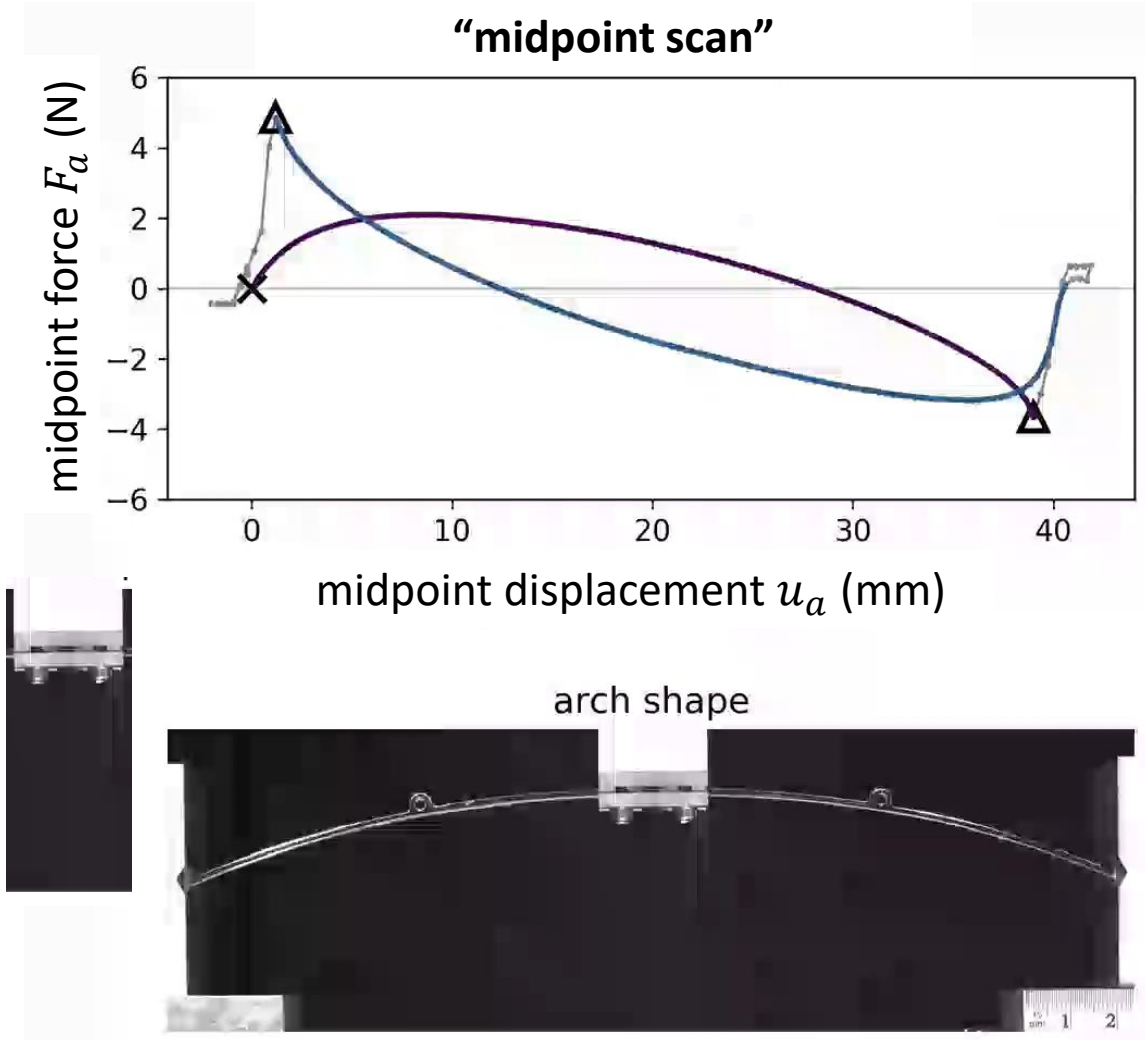
FEA prediction



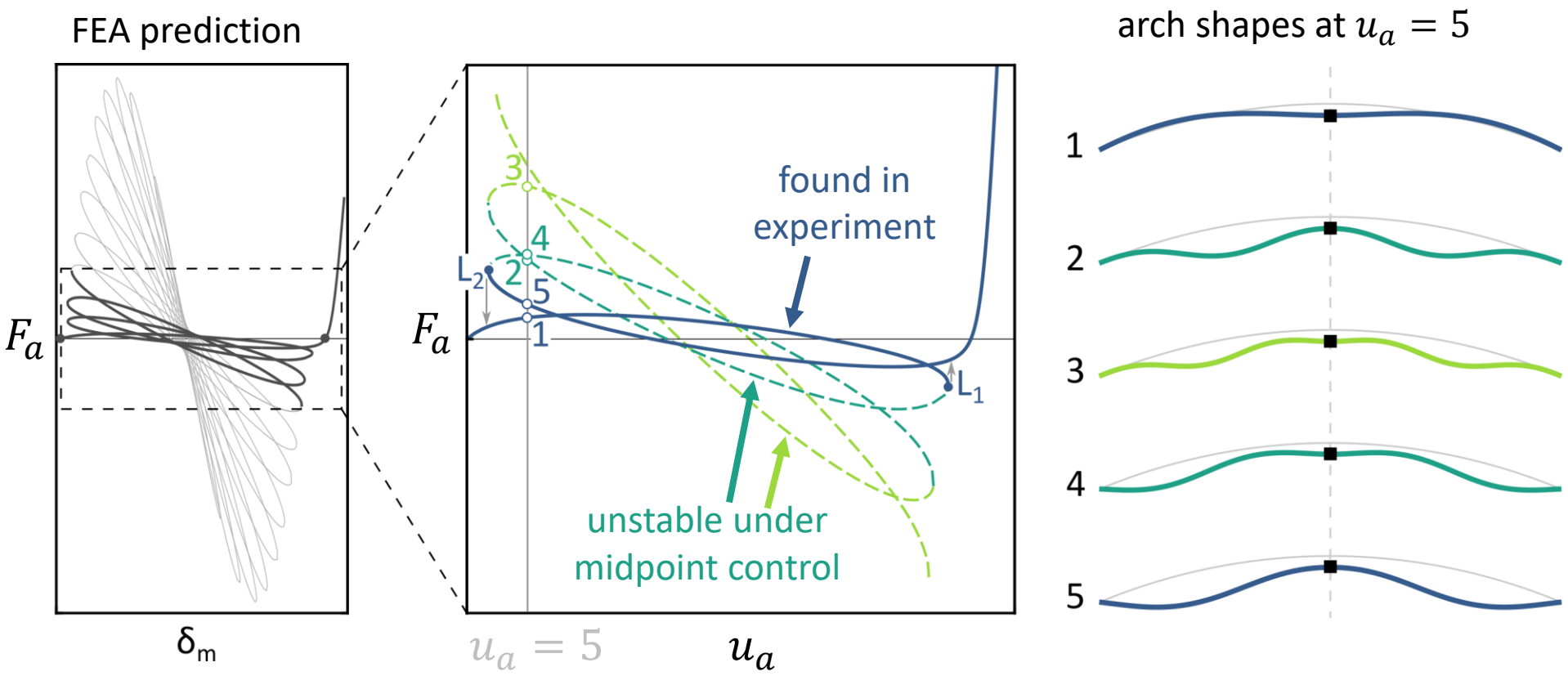
Snap = loss of control over *shape*

- Snap = sudden jump to a different equilibrium (and different shape)
- Control point moves smoothly. *Other* parts of the structure snap.

➔ Insight for solution

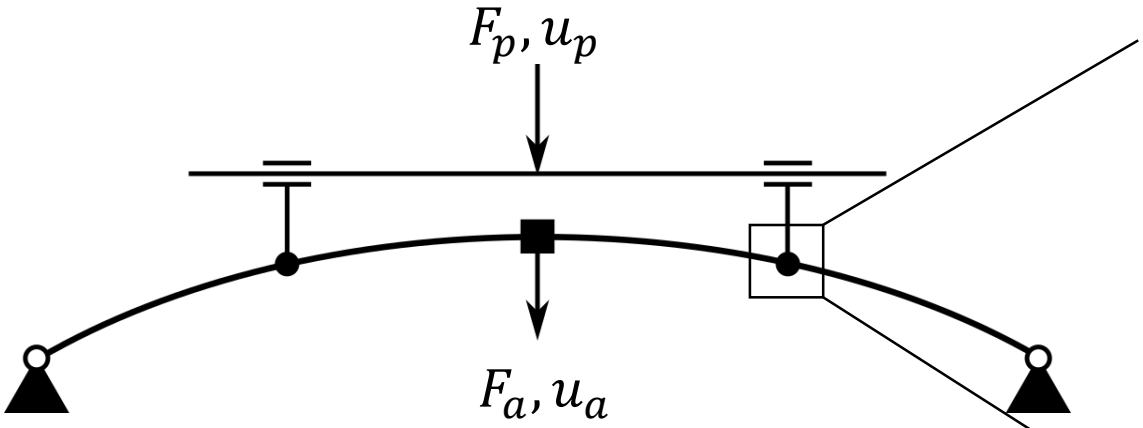


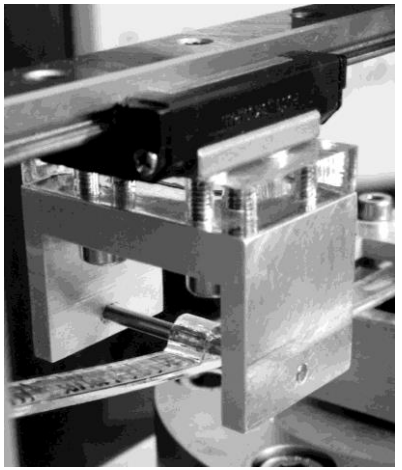
Shape links force & displacement



Shape ***decouples*** force and displacement

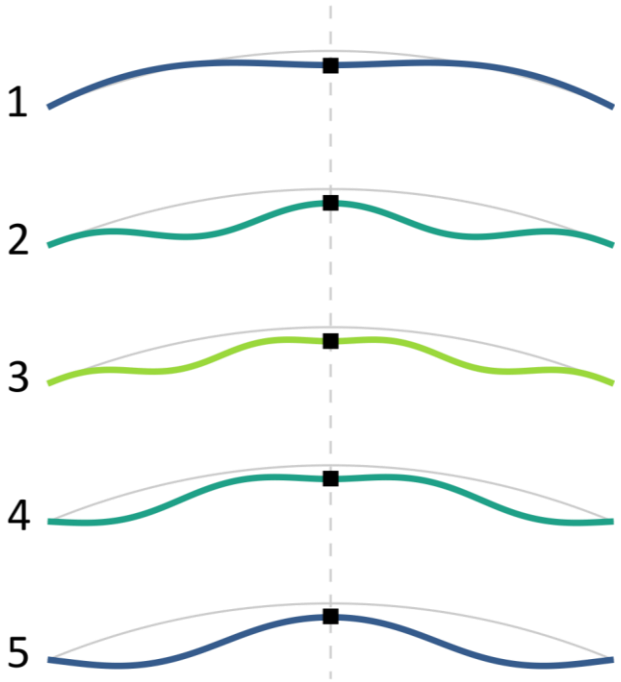
Shape control using extra “probes”

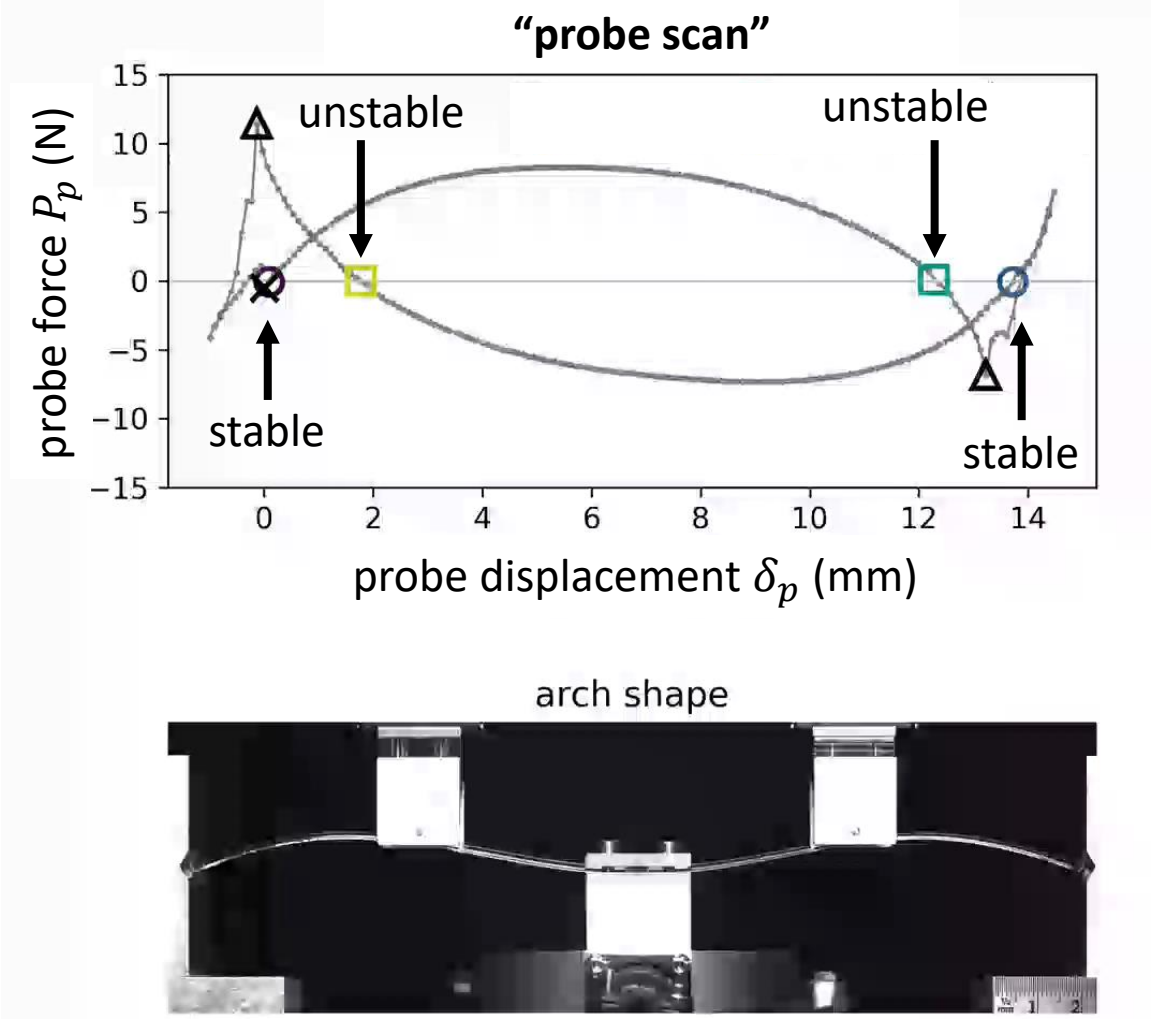




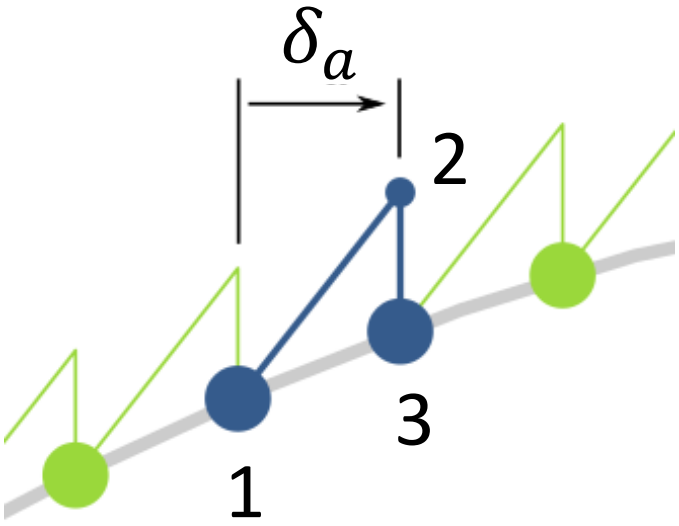
Scanning for other equilibria

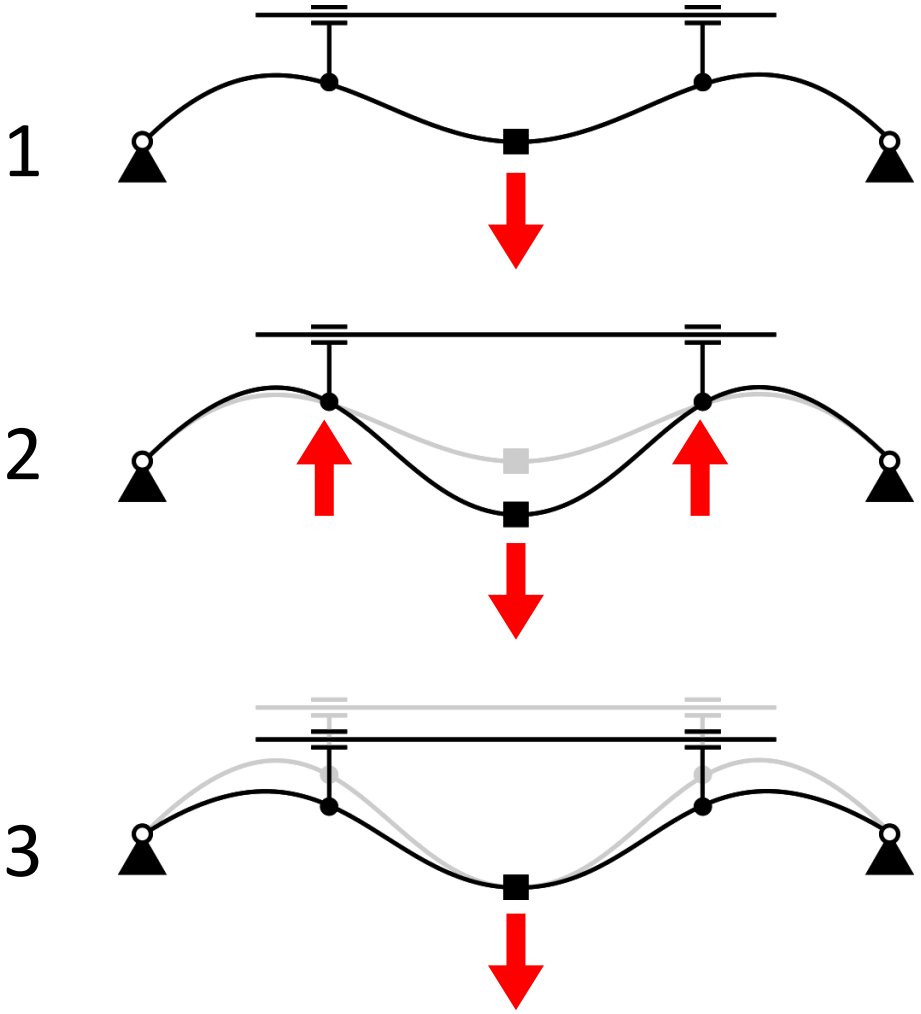
When $F_p = 0$, the probes "don't exist". This is an equilibrium of the unperturbed structure.





Path-following algorithm

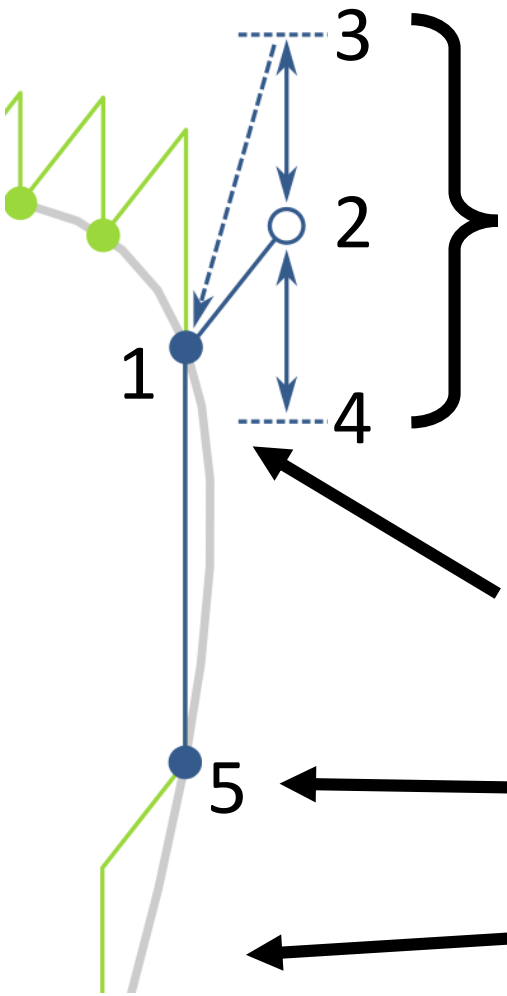




"step-scan":

1) Step actuation point
2) Scan probes until $F_p = 0$

Limit point logic



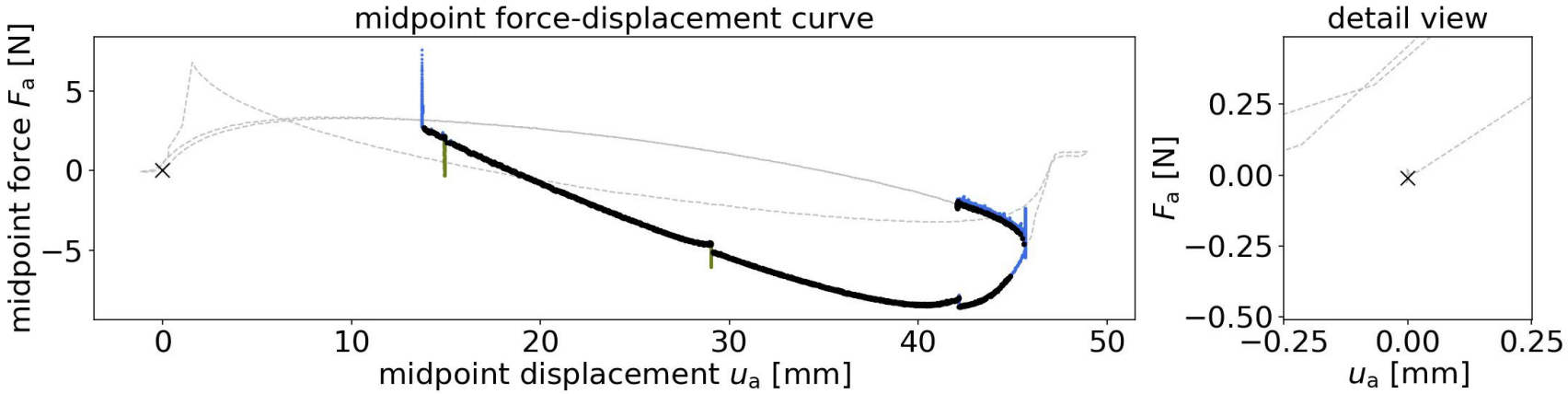
If scans in both directions fail to find an equilibrium

Retreat to last known equilibrium

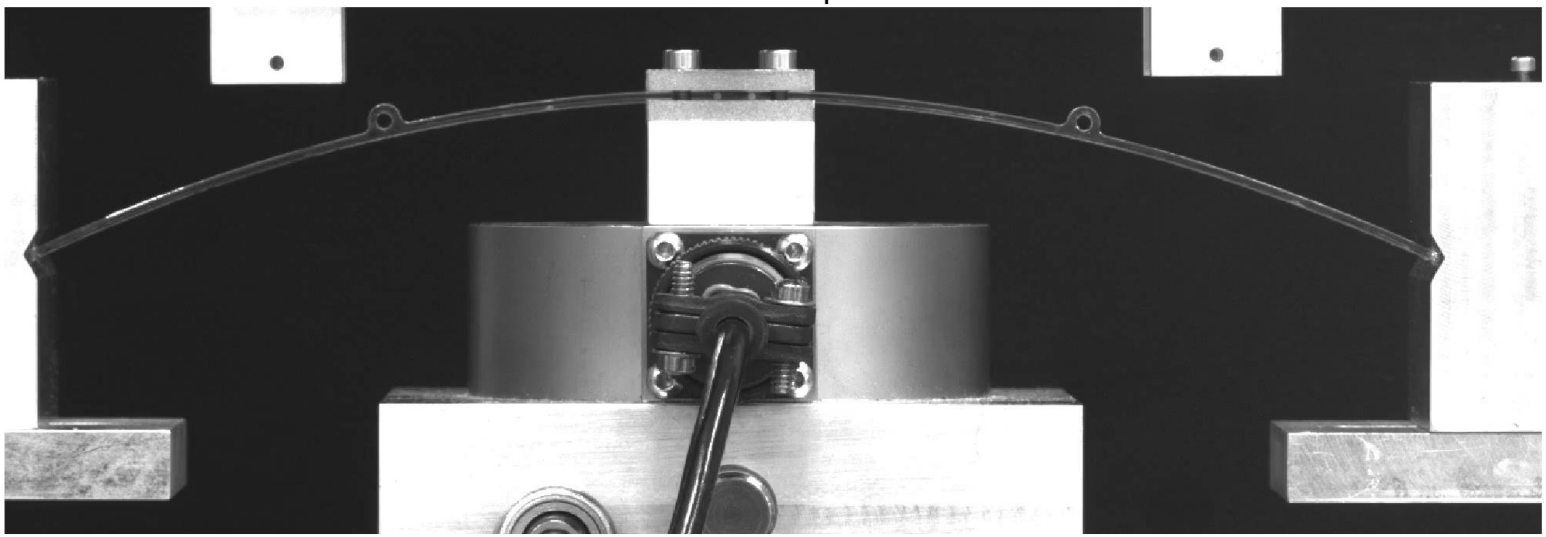
Scan until another equilibrium is found

Start stepping in reverse direction

Step-scan experiments

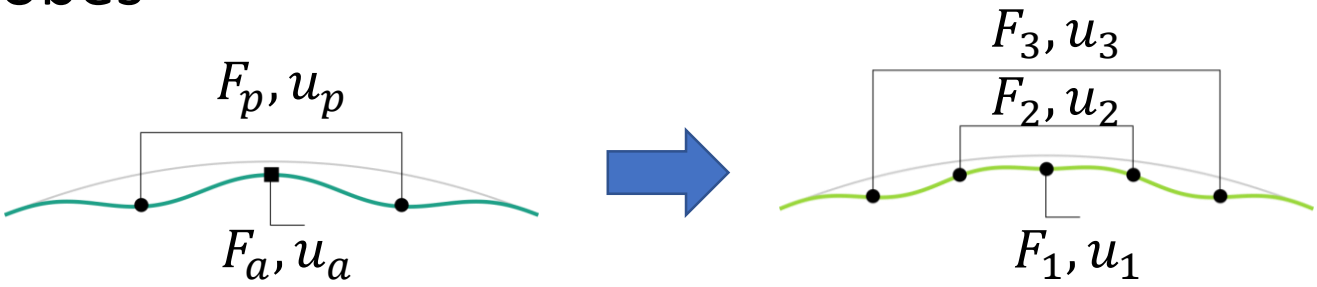


arch shape



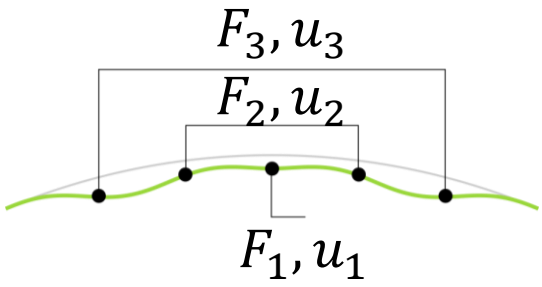
Mark II: tangential stiffness

- Current set-up is “brute force” but robust
- Hard to scale-up to more than one independent probe
- No information about how to coordinate many individual probes



- Ideally want to use an “experimental tangential stiffness” as is the case in numerical methods

Tangential stiffness matrix



Perturb each control point slightly (while fixing all other points) and compute:

$$K_T^{ij} = \frac{\Delta F_i}{\Delta u_j}$$

Δu_j : small increment in position of jth control point

ΔF_i : reaction force at ith control point

Apply standard predictor-corrector scheme of arc length methods:

$$K_T \delta u = -(R + \lambda \widehat{f})$$

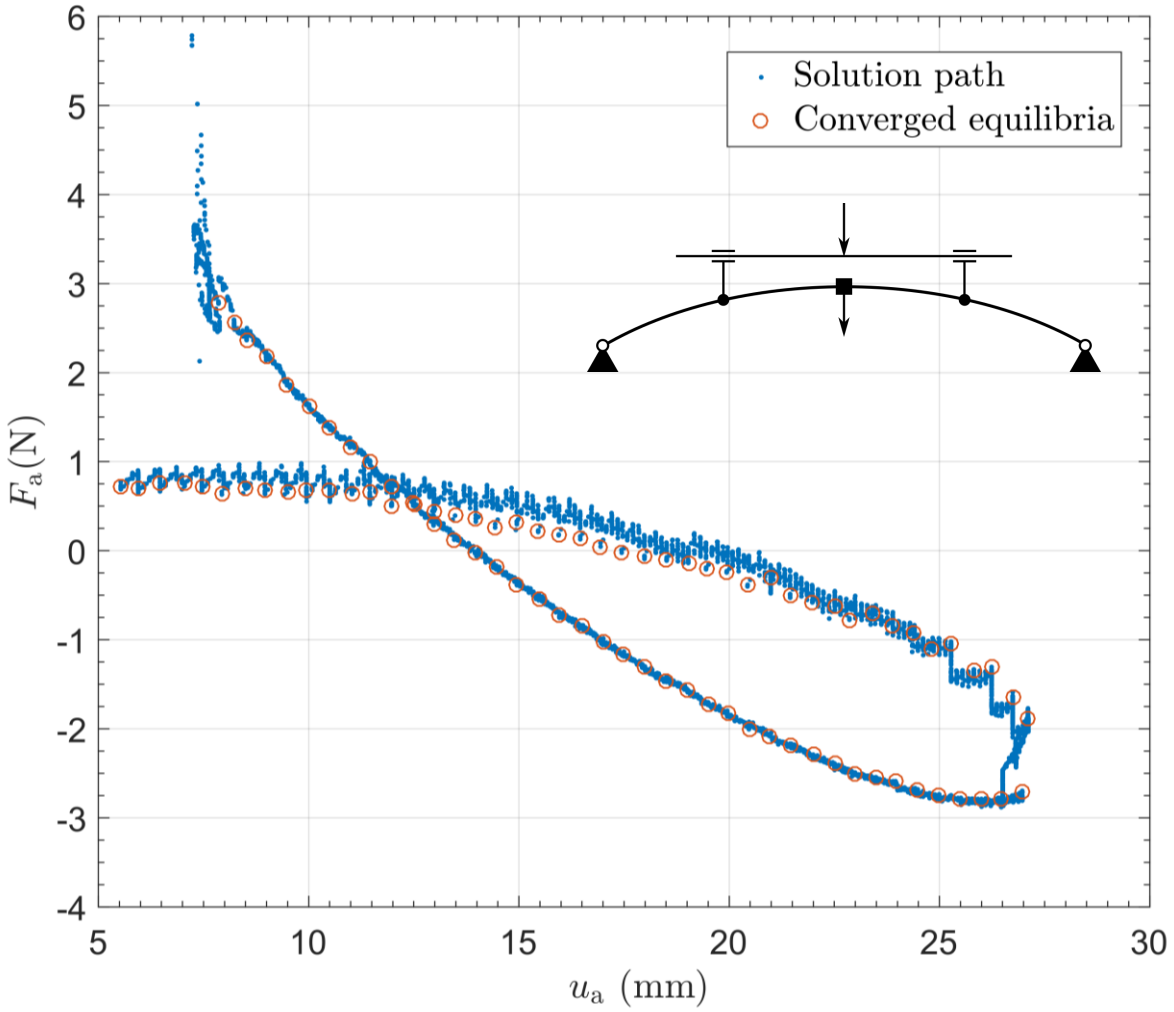
R : residual (out-of-balance) forces

$\hat{f}$: predefined force vector

Iterate until R = 0

(no residual out-of-balance force)

First results: proof of concept



Conclusions

- Demonstrated two procedures to implement experimental path-following:
  - Basic: step-scan
  - Advanced: tangential stiffness
- Both based on idea of *shape control*
  - Stabilises unstable equilibria
  - Allows selection of different equilibria (R=0)
  - Facilitates computation of tangential stiffness
- With the tangential stiffness, computational methods can be replicated

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Thank you for your attention

Questions?

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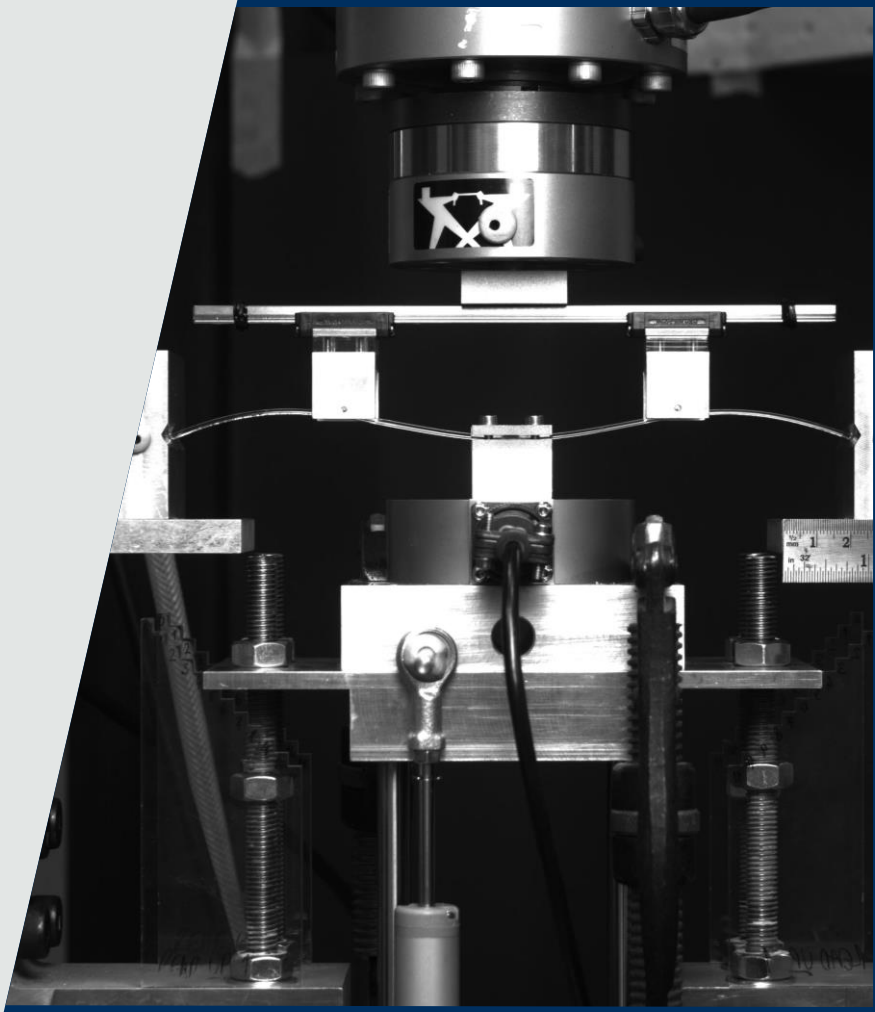

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